Proceedings of the 2003 IEEE
International Conference on Robotics & Automation
Taipei, Taiwan, September 14-19, 2003

Overview of coded light projection techniques for automatic 3D profiling

Jordi Pagès, Joaquim Salvi, Rafael García and Carles Matabosch

Institut d'Informatica i Aplicacions
Universitat de Girona
Av. Lluís Santaló s/n, 17071 Girona (Spain)
{jpages,qsalvi,rafa,cmatabos}eia.udg.es

Abstract— **Obtaining automatic 3D profile of objects is one of the most important issues in computer vision. With this information, a large number of applications become feasible: from visual inspection of industrial parts to 3D reconstruction of the environment for mobile robots. In order to achieve 3D data, range finders can be used. Coded structured light approach is one of the most widely used techniques to retrieve 3D information of an unknown surface. An overview of the existing techniques as well as a new classification of patterns for structured light sensors is presented. This kind of systems belong to the group of active triangulation methods, which are based on projecting a light pattern and imaging the illuminated scene from one or more points of view. Since the patterns are coded, correspondences between points of the image(s) and points of the projected pattern can be easily found. Once correspondences are found, a classical triangulation strategy between camera(s) and projector device leads to the reconstruction of the surface. Advantages and constraints of the different patterns are discussed.**

I. INTRODUCTION

Automatic 3D reconstruction of surfaces is one of the most important topics in computer vision due to its wide field of application. Some examples are range sensoring, quality control of industrial parts, reverse engineering, object recognition and 3D map building. Therefore, 3D reconstruction not only can be applied to industrial manufacturing, but also to robotic perception.

Among all the ranging techniques, stereovision is based on imaging the scene from two or more known points of view and then finding pixel correspondences between the different images in order to triangulate the 3D position. Triangulation is possible if cameras are calibrated [20]. However, difficulties to find the correspondences arise even taking into account epipolar constraints. Coded structured light consists of substituting one of the cameras by a device that projects a light pattern onto the surface. Since each point in the pattern is encoded in a certain way that identifies its coordinates, the correspondence problem is solved with no geometrical constraints. In stereovision, the correspondence problem only becomes feasible when the surfaces are textured or there are singular points easily distinguishable like image corners. Moreover, while with stereovision only few points will be probably matched, with an appropriate light pattern correspondences of a large number of pixels can be found. Thus, coded structured light may be used as a solution to simplify the inherent problem of finding correspondences in classical stereovision systems.

This paper presents a comprehensive survey on coded structured light techniques, which updates the discussions presented in [1]. The aim of this work is to present a consistent and definitive classification of the bibliography related to this topic, in order to find quickly which technique is more suitable to each measuring surface and environmental conditions. This article is structured as follows: in section II, an exhaustive classification is presented. Then, sections III, IV and V explains the features of the most relevant methods. In section VI, conclusions are discussed.

II. CLASSIFICATION OF CODED PATTERNS

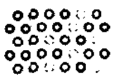
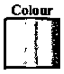
Pattern projection techniques differ in the way how each point is identified in the pattern, *i.e.* what kind of codeword is used, and whether it encodes both axis or just one. In fact, it is only necessary to encode one axis, since a 3D point can be obtained either from intersecting two lines or intersecting a line with a plane. The second option is exploited by all those authors that propose row or column coded patterns.

In Table I the surveyed pattern projection techniques are classified according to their codification strategy. The features indicating if a pattern is suitable to measure moving objects or not, the considered color depth and whether repeated codewords appear (periodical coding) or not (absolute coding) are all indicated in the seven columns at the right side of the table.

The first division among techniques differentiates between patterns based on a spatial, temporal (time-multiplexing) and direct codification. The first type refers to those whose points are coded with the information included in a neighborhood around them. Time-multiplexing strategy is based on assigning a sequence of values to every pattern pixel along time. While direct codification means that each point of the pattern is identified just by itself.

TABLE I

THE PROPOSED CLASSIFICATION

			Scene applicability: *Static*	Scene applicability: *Moving*	Pixel depth: *Binary*	Pixel depth: *Grey levels*	Pixel depth: *Colour*	Coding strategy: *Periodical*	Coding strategy: *Absolute*
Spatial neighborhood	Non-formal codification	Maruyama and Abe		√	√			√	
		Durdle et al.		√		√		√	
		Ito and Ishii		√		√			√
		Boyer and Kak		√			√		√
		Chen et al.		√			√		√
	De Bruijn sequences 	Hügli and Maître		√			√		√
		Monks et al.		√			√		√
		Vuylsteke and Oosterlinck		√	√				√
		Salvi et al.		√			√		√
		Lavoie et al.		√			√		√
		Zhang et al.	√	√			√		√
	M-arrays 	Morita et al.	√		√				√
		Petriu et al.		√	√				√
		Kiyasu et al.		√	√				√
		Spoelder et al.		√	√				√
		Griffin and Yee		√	√		√		√
		Davies and Nixon		√			√		√
		Morano et al.	√		√		√		√
Time-multiplexing	Binary codes 	Posdamer et al.	√		√				√
		Inokuchi et al.	√		√				√
		Minou et al.	√		√				√
		Trobina	√		√				√
		Valkenburg and McIvor	√		√				√
		Skocaj and Leonardis	√		√				√
		Rocchini et al.	√				√		√
	n-ary codes	Caspi et al.	√				√		√
		Horn and Kiryati	√			√			√
	Gray code + Phase shifting	Bergmann	√			√			√
		Sansoni et al.	√		√				√
		Wiora	√			√			√
		Gühring	√		√				√
	Hybrid methods	Kosuke Sato	√		√	√			√
		Hall-Holt and Rusinkiewicz		√	√				√
Direct coding	Grey levels	Carrihill and Hummel	√			√			√
		Chazan and Kiryati	√			√			√
		Hung		√		√		√	
	Colour 	Tajima and Iwakawa	√				√		√
		Smutny and Pajdla	√				√		√
		Geng		√			√		√
		Wust and Capson		√			√	√	
		Tatsuo Sato	√				√	√	

III. SPATIAL NEIGHBORHOOD

This subgroup of techniques tend to concentrate all the coding scheme in a unique pattern. The codeword that labels each pixel is obtained from a neighborhood of pixels around it. In most cases they are suitable for measuring moving surfaces. However, the decoding stage is more difficult because the whole neighborhood can not always be recovered due to occlusions and shadows. The following subsections summarize the most common codification theories used for spatial coding.

A. *Non-formal codification*

The first authors exploiting spatial neighborhood did not use any formal codification theory in order to define the codewords represented in every neighborhood. Such patterns were usually generated by brute-force algorithms accomplishing some constraints. Different techniques belonging to this group can be found in the bibliography. They basicall differ in the visual features used to identify every neighborhood of the patterns.

For example, the pattern proposed by Boyer and Kak [3] is formed by vertical slits coded with four colors separated by black bands. The sequence of color slits was designed so that if the pattern is divided in subpatterns of a certain length, none is repeated. The most interesting of this idea is the decoding stage. Boyer and Kak realized that the morphology of the measuring surface acts as a perturbation applied to the projected pattern, so the received pattern can contain disorders or even deletions of the slits. In order to match each received slit with the corresponding projected one a four-steps algorithm was designed. First, each subpattern is sliced along the received pattern to find the best matching position. Secondly, a region growing process of the matched subpatterns is fulfilled trying to cover as much correspondences of slits as possible. Thirdly, a fitting stage is done in order to remove erroneous matchings. When two subpatterns overlap, the thinnest is cut so the shared slits are only associated with the largest one. Finally, an stage of indexing the matched slits is done. As can be seen, the essence of the method is a subpattern or template matching process. The drawback of these methods is the complex algorithms involved to decode the patterns, which do not guarantee the best solution.

Ito [13] proposed a grid pattern where each cell was painted with a grey level chosen from a set of three values. The coded points of the pattern are the intersections of the grid lines. The codeword assigned has a length of 16 values, where each of them refers to one of the grey levels used. This codeword is composed of the subcodewords of the grid point that is being considered in addition to the subcodewords of its four adjacent neighbors. The subcodeword of a point is an ordered sequence of the values associated to the four cells that envelop that point. However, Ito did not proposed a general algorithm to generate such a pattern.

Chen et al. [7] defined a pattern consisting of a sequence of colored vertical stripes separated by black bands. An algorithm was designed in order to generate the pattern. The aim of the algorithm is to obtain a pattern such that the correlations between any two consecutive color subsequences are small enough. The algorithm is based on the trial-and-error approach and operates in the HSI (Hue, Saturation and Intensity) color space. The I component of each stripe is fixed randomly by the program and then the H and S components are chosen in order to obtain a sequence with minimum autocorrelation.

Maruyama and Abe [16] designed a pattern composed of vertical slits with random cuts. The position of all the cuts of a given slit differentiates that slit from all the rest. The way a segment of a slit is identified is the codeword formed by the longitude of this segment and the longitudes of the six adjacent segments (the upper, lower, upper left, upper right, lower left and lower right segments). This pattern only worked well with very smooth surfaces.

B. Patterns encoded with De Bruijn sequences

The techniques presented in the previous subsection had lack of robustness since repeated neighborhoods could appear, i.e. uniquess of codewords is not enssured. This problem was solved for those authors who realized that *De Bruijn sequences* are very useful to encode patterns based on spatial neighborhood. A *De Bruijn sequence* of order m over an alphabet of n symbols is a circular string of length n^m that contains each substring of length m exactly once. Similarly, a *pseudorandom sequence* or a *m-sequence* has a length of $n^m - 1$ because it does not contain the substring formed by 0's [15]. This sort of sequences can be obtained searching *Eulerian cycles* or *Hamiltonian cycles* over different kinds of *De Bruijn graphs* [8].

Pseudorandom sequences have been used for encoding patterns based on column or row slits and grid patterns. In all the cases the codification is unidimensional. A multslit pattern was proposed by Zhang et al. [27], who also defined a decoding stage very robust based on multi-pass dynamic programming. An example of pattern consisting of a sequence of 64 vertical colored slits encoded with a De Bruijn sequence of order 3 and 3 colors is shown in Fig. 1b. Salvi et al. [21] proposed a grid pattern of 29×29 orthogonal slits, see 1c. Columns and rows were color encoded with the same De Bruijn sequence of third order over an alphabet of three symbols. Three different colors were used to encode the columns and rows, respectively. The rest of techniques of this group follow one of these two pattern representations, and differ in the complexity and robustness of the decoding stage. The grid patterns are more reliable because a redundant codification for each point is present, which allows some decoding errors to be detected and even corrected.

C. Patterns encoded with M-arrays

The extension of the *pseudorandom sequences* to the bidimensional case has also been used to encode patterns. Let M be a matrix of dimensions $r \times v$ where each element is taken from an alphabet of k symbols. If M has the window property, i.e. each different window of dimensions $n \times m$ appears exactly once, then M is a *perfect map*. If M contains all submatrices of $n \times m$ except the one filled by 0's, then M is called a *M-array* or a *Pseudorandom array*. For more information see [15].This kind of arrays have been widely used in pattern codification because the window property allows every different submatrix to be associated to an absolute position in the array.

The main differences among these methods focus in the way the elements of the array are represented in the pattern. Using arrays to encode a pattern means that a bidimensional coding scheme is being used, because each point of the pattern has two different codewords. Therefore, both rows and columns are encoded. Yee and Griffin [26] defined a process to construct an array using an alphabet of four symbols. The resulting array has the property that the position of an ellement is defined by the codeword formed by the value of itself and the values of its four neighbors. This method is suitable for dynamic environments as a matter of a single pattern is projected. Vuylsteke and Ooesterlick [25] presented a binary M-array with a window property of 2×3, painted in the pattern using two different shape primitives. The rest of methods cited in the table use M-arrays where each element is represented by spots whose values are coded in black and white or using color (see Fig. 1d). One of the most interesting approaches is given by Morano et al. [18]. The authors proposed a general method to construct an M-array fixing the length of the alphabet, the window property size, the dimensions of the array and the Hamming distance between each window. Usually all the previous methods worked with a Hamming distance of one, which did not allow error correction.

IV. TIME-MULTIPLEXING

The most exploited coded patterns are based on temporal coding. In this case, a set of patterns are successively projected onto the surface. The codeword for a given pixel is usually formed by the sequence of illuminance values for that pixel across the projected patterns. The main constraint of temporal systems is their inapplicability to dynamic scenes. Some authors prefer to call this technique spatio-temporal codification.

This kind of patterns can reach a high accuracy in the measurements. This fact relies on two points: first, a small set of colors or grey levels are used, so they are easily distinguishable; second, a coarse-to-fine paradigm is followed, since the position of a pixel is being encoded more precisely by the time the patterns are projected. In addition, large resolution can be achieved.

A. Patterns based on binary codes

Black and white are used to encode every pattern point. Column codification is used in these approaches. Posdamer et al. [19] were the first who proposed the projection of a sequence of m patterns to encode 2^m stripes using a plain binary code. Thus, the codeword associated to each pixel is the sequence of 0s and 1s obtained from the m patterns. Valkenburg and McIvor [24] decreased the measuring error using Gray code and estimating the position of the stripes with subpixel accuracy. An example of the initial binary patterns of a sequence encoded with Gray code is shown in Fig. 1a.Minou et al. [17] proposed the use of Hamming code in order to detect errors and even correcting them increasing the length of the codewords, i.e. the number of projected patterns.

B. Patterns based on n-ary codes

Caspi et al. [5] proposed an extension of Gray code using an alphabet of n symbols (where each symbol is associated to a color). The work of Caspi et al. is very important since is the most robust generalization of the binary coded patterns. Caspi et al also defined an illumination model that takes into account the surface reflectivity and the transmittance spectrum of the projector and the camera spectral response. Moreover, an adaptative system was designed, completely reconfigurable depending on the measuring scene and the work conditions. The parameters of the system are the number of patterns, the number of colors and the desired immunity to noise. If two of the parameters are chosen, the remaining one is automatically set.

The same n-ary codewords were used by Horn and Kiryati [11], but mapping every symbol of the alphabet to a different grey level. The performance of the system was tested and compared with typical Gray code techniques, showing a better accuracy in the experiments.

In general, n-ary techniques are useful to obtain similar or even better performance that with binary codes, but reducing a lot the number of patterns.

C. Gray code and Phase shifting

This methodology is based on the classical line stripe scanning over time, which constitutes the paradigm of the structured light sensors. These systems are based on scanning the surface by projecting a light stripe and grabbing an image for every position of the rotating laser. Knowing each laser projection angle, triangulation can be fulfilled for every imaged stripe position. In order to minimize the scanning time, some authors realized that a slide projector can project a multistripe pattern onto the scene. However, a new problem of ambiguities arose: how to distinguish among all the projected stripes.

Krattenhaler et al. [14] introduced the idea to combine a multristripe pattern with a previous stage of Gray code projection in order to solve the problem of ambiguities among stripes. The Gray code patterns allow the identification of a set of regions in the image plane where only a stripe is allowed to appear. Then, when a stripe is located in the grabbed image, its corresponding position in the pattern is known thanks to the Gray codeword previously associated to that part of the image.

Gühgring [9] used the same principle adding phase shifting. Hence, instead of projecting a single pattern with several equidistant stripes after the Gray code stage, a set of patterns can be used where the position of the stripes is consecutively shifted. With these additional patterns the resolution of the system is increased. He besides introduced subpixel location of the stripes in order to increase the accuracy of the system. The method of Bergman [2] uses a continuous sine wave of grey levels periodically repeated along the pattern. The resolution incrases since all the columns of the pattern are encoded with different grey levels.

These techniques can obtain high accuracy (about 40μm of mean error), but the large number of required patterns must also be considered.

D. Hybbrid methods

There are some techniques mainly based on the projection of multiple encoded patterns along time. However, if they also take into account a small spatial neighborhood of pattern points in the codification strategy they can be considered as hybrid methods.

Hall-Holt and Rusinkiewicz [10] divided four patterns in a total of 111 vertical stripes that are painted in white or black. Codification is located at the boundaries of each pair of stripes. The codeword of each boundary is formed by 8 bits. Every pattern gives 2 of these bits, representing the value of the bounding stripes. Therefore, the technique used time-multiplexing (since 4 coded patterns are projected) and also spatial coding (a neighborhood of 2 stripes is considered in every pattern). Moving scenes are supported, something really strange in the time-multiplexing paradigm, thanks to an stage of boundary tracking along the patterns. However, the movement must be slow.

V. DIRECT CODIFICATION

There are some ways to create a pattern such that every pixel coordinates can be directly obtained by the information represented on it. In order to achieve this, it is necessary to use either a large range of color values or reducing this range and introducing periodicity in the pattern. In theory, a high resolution of 3D information can be obtained, however, the sensitivity to noise is very high because the "distance" between "codewords", i.e. the colors used, is very small. Moreover, in order to eliminate the color of the objects is necessary, in most cases, to take one or more reference images. Therefore, these techniques are not typically suitable for dynamic scenes. However, the number of patterns is still far from the required using time-multiplexing and smooth surface assumptions are not required like in the case of spatial neighborhood. Direct codification is usually constrained to neutral color objects or not highly saturated colors. Besides, it is necessary to tune the system in order to perceive and correctly identify the whole spectrum of projected colors.

A. Coding based on grey levels

Carrihill and Hummel [4] developed the intensity ratio sensor. A linear wedge spread along vertical columns containing a large number of grey levels from black to white was proposed. The observed grey level of a given pixel in the image is divided by the value of the same pixel under constant illumination in order to obtain a ratio that permits to identify the column of the pattern that has projected there. Chazan and Kiryati [6] presented an extension of Carrihill's technique which was called the sawtooth sensor, based on multiple wedge patterns. In the first pattern the gradient spreads along all columns, while in the following patterns its frequency is consecutively increased. Like in all the patterns that present periodicity, the problem of ambiguities must be solved. In this case, the grey level of a pixel in the previous projected pattern identifies in which period of the current projected pattern belongs such a pixel. Advantages of this technique is high resolution and better accuracy if the camera and projector can be tunned so that a linear ratio is obtained in the images. The sawtooth sensor is less sensitive to noise than Carrihill's sensor since in the last projected pattern the number of different grey levels projected is smaller, so it is easy to differentiate all them in the camera images.

Hung [12] created a grey level pattern sinusoidally encoded. The reconstruction principle relies on the fact that the period of the observed pattern projected in the scene increases proportionally to the distance, hence the frequency decreases. The frequency of the signal in a given pixel can be estimated with the phase variation of the observed pattern between two consecutive pixels. Once the phase variation and the frequency are calculated and assuming that the projector and the camera have been calibrated, the depth of the point corresponding to the pixel is easily obtained. It must be noted that the technique was only tested with synthetic images containing gaussian noise. Real experiments should be fulfilled in order to test the robustness of the pattern.

B. Color based coding

The methods belonging to this group use the same principle than the ones above, however, color is used instead of grey levels. Tajima and Iwakawa [23] presented the rainbow pattern. A large set of vertical slits are encoded with a different wavelength, so a large sampling of the spectrum from red to blue is used. The images are grabbed by a monochromatic camera. Two images of the scene are taken through two different color filters. Calculating the ratio between both images an index for every pixel is obtained that neither depends on illumination, nor on the color of the scene. In order to obtain good results, monochromatic cameras with large sensitivity (about 11 bits per pixel) were used.In 1999, Sato presented the *multispectral pattern projection range finder* [22]. In this work, the author discussed the complicated optical system required for the rainbow range finder of Tajima. Sato proposed a new technique that only needs an LCD projector and a CCD camera. Moreover, the new technique could cancel the color of the measuring surface, so the results were not affected by the spectral reflectance of the surface. The technique consisted of projecting a periodic rainbow pattern 3 times, shifting the hue phase 1/3 of its period in every projection (see Fig. 1e). An extra image was synthesized by a certain linear combination of the three grabbed images. Afterwards, Sato demonstrated that the Hue value of every pixel of the synthesized image is equal to the projected Hue value in the first pattern. Therefore, correspondences between synthesized image pixels and projected rainbow columns can be done. In order to get a good resolution, the pattern had to be periodic, so the identification of the periods is a key point in the decoding stage.

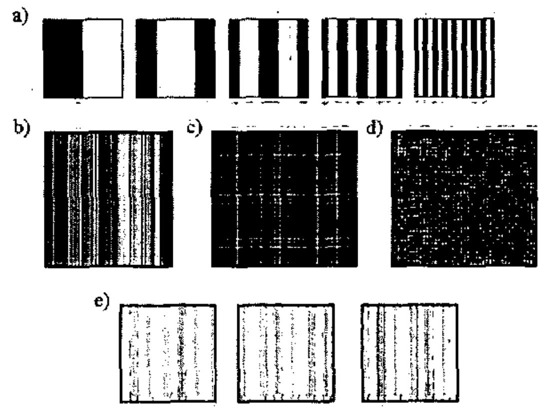


Fig. 1. Examples of patterns; a) Time-multiplexing based on a sequence of Gray coded patterns; b) Pattern of vertical colored slits encoded with a De Bruijn sequence; c) Grid pattern with De Bruijn sequence codification; d) Pattern of colored dots encoded with an M-array; e) Direct codification using three shifted periodic rainbow patterns.

VI. CONCLUSIONS

An exhaustive classification of coded structured light techniques has been presented. This kind of techniques are suitable to reconstruct the 3D profile of surfaces and therefore, it can be applied from industrial inspection to robot perception. The classification principle is based on the pattern coding strategies. Techniques based on time-multiplexing have generally demonstrated high accuracy, large resolution and an easy decoding stage as only a reduced set of colors is used (often black and white). However, its main constraint is their inapplicability to moving surfaces since multiple patterns must be projected. A way to solve this problem is to identify each pattern point by a certain spatial neighborhood or increasing the number of colors used. The larger the number of colors, the smaller the required neighborhood, in spite of a harder segmentation complexity. When using spatial neighborhood a unique pattern can be defined so that moving surfaces can be measured. However, discontinuities over surfaces can produce false identification of certain pattern regions. Moreover, since the codification is condensed in a unique pattern, the maximum resolution is lower. Another way to reduce the number of patterns is using the maximum grey level or color spectrum, so that each column or row of the pattern has its own value. This solution, however, is only recommended when dealing with neutral color scenes. It is necessary to find a trade off between the number of patterns to project and the number of colors or grey levels used to encode, which is also related to the acquisition time and the accuracy that can be obtained.

In summary, if the objective is to obtain high accuracy and dealing with static scenes, time-multiplexing is the most suitable. Moreover, the most complete techniques are the ones proposed by Caspi et al. [5] and Guhring [9]. When dealing with dynamic surfaces, the patterns based on M-arrays or pseudorandom sequences are recommended. The difficulty relies on designing a decoding algorithm robust enough to take into account discontinuities in the perceived pattern. The most robust solution to this problem has been proposed by Zhang et al. [27].

The whole list of references can be found in *http://eia.udg.es/~jpages/coded_light.*

VII. ACKNOWLEDGMENTS

Work funded by Spanish project CICYT TAP99-0443-C05-01.

VIII. REFERENCES

[1] J. Batlle, E. Mouaddib, and J. Salvi. Recent progress in coded structured light as a technique to solve the correspondence problem: a survey. *Pattern Recognition*, 31(7):963–982, 1998.

[2] D. Bergmann. New approach for automatic surface reconstruction with coded light. In *Proceedings of Remote Sensing and Reconstruction for Three-Dimensional Objects and Scenes*, volume 2572, pages 2–9. SPIE, August 1995.

[3] K. L. Boyer and A. C. Kak. Color-encoded structured light for rapid active ranging. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 9(1):14–28, 1987.

[4] B. Carrihill and R. Hummel. Experiments with the intensity ratio depth sensor. In *Computer Vision, Graphics and Image Processing*, volume 32, pages 337–358. Academic Press, 1985.

[5] D. Caspi, N. Kiryati, and J. Shamir. Range imaging with adaptive color structured light. *Pattern analysis and machine intelligence*, 20(5):470–480, May 1998.

[6] G. Chazan and N. Kiryati. Pyramidal intensity-ratio depth sensor. Technical report 121, Center for Communication and Information Technologies, Department of Electrical Engineering, Technion, Haifa, Israel, October 1995.

[7] C. Chen, Y. Hung, C. Chiang, and J. Wu. Range data acquisition using color structured lighting and stereo vision. *Image and Vision Computing*, 15:445–456, 1997.

[8] H. Fredricksen. A survey of full length nonlinear shift register cycle algorithms. *Society of Industrial and Applied Mathematics Review*, 24(2):195–221, 1982.

[9] Jens Gühring. Dense 3-d surface acquisition by structured light using off-the-shelf components. *Videometrics and Optical Methods for 3D Shape Measurement*, 4309:220–231, 2001.

[10] O. Hall-Holt and S. Rusinkiewicz. Stripe boundary codes for real-time structured-light range scanning of moving objects. In *The 8th IEEE International Conference on Computer Vision*, pages II: 359–366, 2001.

[11] E. Horn and N. Kiryati. Toward optimal structured light patterns. *Image and Vision Computing*, 17(2):87–97, February 1999.

[12] D.C.D. Hung. 3d scene modelling by sinusoid encoded illumination. *Image and Vision Computing*, 11:251–256, 1993.

[13] M. Ito and A. Ishii. A three-level checkerboard pattern (tcp) projection method for curved surface measurement. *Pattern Recognition*, 28(1):27–40, 1995.

[14] W. Krattenthaler, K. J. Mayer, and H. P. Duwe. 3D-surface measurement with coded light approach. In *Proceedings Öesterr. Arbeitsgem. MustererKennung*, volume 12, pages 103–114, 1993.

[15] F. J. MacWilliams and N. J. A. Sloane. Pseudorandom sequences and arrays. *Proceedings of the IEEE*, 64(12):1715–1729, 1976.

[16] M. Maruyama and S. Abe. Range sensing by projecting multiple slits with random cuts. *Pattern Analysis and Machine Intelligence*, 15(6):647–651, June 1993.

[17] M. Minou, T. Kanade, and T. Sakai. A method of time-coded parallel planes of light for depth measurement. *Transactions of the IECE of Japan*, 64:521–528, 8 1981.

[18] R. A. Morano, C. Ozturk, R. Conn, S. Dubin, S. Zietz, and J. Nissanov. Structured light using pseudorandom codes. *Pattern Analysis and Machine Intelligence*, 20(3):322–327, March 1998.

[19] J. L. Posdamer and M. D. Altschuler. Surface measurement by space-encoded projected beam systems. *Computer Graphics and Image Processing*, 18(1):1–17, 1982.

[20] J. Salvi, X. Armangué, and J. Batlle. A comparative review of camera calibrating methods with accuracy evaluation. *Pattern Recognition*, 35(7):1617–1635, 2002.

[21] J. Salvi, J. Batlle, and E. Mouaddib. A robust-coded pattern projection for dynamic 3d scene measurement. *International Journal of Pattern Recognition Letters*, (19):1055–1065, September 1998.

[22] T. Sato. Multispectral pattern projection range finder. In *Proceedings of the Conference on Three-Dimensional Image Captuer and Applications II*, volume 3640, pages 28–37, San Jose, California, January 1999. SPIE.

[23] J. Tajima and M. Iwakawa. 3-D data acquisition by rainbow range finder. In *International Conference on Pattern Recognition*, pages 309–313, 1990.

[24] R. J. Valkenburg and A. M. McIvor. Accurate 3d measurement using a structured light system. *Image and Vision Computing*, 16(2):99–110, February 1998.

[25] P. Vuylsteke and A. Oosterlinck. Range image acquisition with a single binary-encoded light pattern. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 12(2):148–163, 1990.

[26] S. R. Yee and P. M. Griffin. Three-dimensional imaging system. *Optical engineering*, 6(33):2070–2075, 1994.

[27] L. Zhang, B. Curless, and S. M. Seitz. Rapid shape acquisition using color structured light and multi-pass dynamic programming. In *Int. Symposium on 3D Data Processing Visualization and Transmission*, Padova, Italy, June 2002.